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Overview: Development of the National Ignition Facility and the transition to a User Facility for the Ignition Campaign and a Wide Range of High Energy Density Scientific Research

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OVERVIEW: DEVELOPMENT OF THE NATIONAL IGNITION FACILITY AND THE TRANSITION TO A USER FACILITY FOR THE IGNITION CAMPAIGN AND HIGH ENERGY DENSITY SCIENTIFIC RESEARCH

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ABSTRACT

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) has been operational since March 2009 and has been transitioning to a user facility supporting ignition science, high-energy-density stockpile science (HEDSS), national security applications, and fundamental science. The facility has achieved its design goal of 1.8 MJ and 500 TW of 3ω light on target, and has performed target experiments with 1.9 MJ at peak powers of 410 TW. The National Ignition Campaign (NIC), established by the U.S. National Nuclear Security Administration (NNSA) in 2005, was responsible for transitioning the NIF from a construction project to a national user facility. Besides the operation and optimization of the use of the NIF laser, the NIC program was responsible for developing capabilities including target fabrication facilities; cryogenic layering capabilities; over 60 optical, x-ray, and nuclear diagnostic systems; experimental platforms; and a wide range of other NIF facility infrastructure. This article provides a summary of some of the key experimental results on the NIF to date, an overview of

the NIF facility capabilities, and the challenges that were met in achieving these capabilities. They are covered in more detail in the articles that follow.

Keywords: National Ignition Facility, National Ignition Campaign, High Energy Density Science, National User Facility

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I. INTRODUCTION

The possibility of imploding small tritium/deuterium-filled fuel capsules to produce mini-fusion explosions was explored soon after the first thermonuclear explosions in the early 1950s. Various technologies have been studied in pursuit of the extreme energy density required for laboratory-scale fusion. Each technology has significant challenges. For example, electron and ion beams that can deliver the required energy must contend with Coulomb repulsion forces that make focusing these beams onto a small target a daunting challenge. The demonstration in 1960 of the first laser, a ruby laser, provided a new option. Energy from laser beams can be focused and deposited within a small volume and the challenge for scientists and engineers became, “Can a practical laser system be constructed that can deliver the energy and power required by the fuel while, at the same time, meeting all of the other demands for achieving a high-temperature, high-density, symmetric implosion?”[1,2,3,4,5,6]

Laser Inertial Confinement Fusion (ICF) relies on either x rays (Indirect Drive) or electron conduction (Direct Drive) for energy transport to drive the implosion of a capsule containing thermonuclear fuel. For Indirect Drive (ID), the laser energy is absorbed in a high-Z enclosure, a “hohlraum”, which surrounds the capsule containing the fuel. The hohlraum material heated by the laser emits x rays that are absorbed on the fuel capsule to drive the implosion. For Direct Drive (DD), the laser beams are aimed directly at the capsule. The laser energy is transferred to electrons by means of inverse bremsstrahlung or other laser plasma interaction (LPI) collective processes, and electron conduction drives the implosion. At thermonuclear ignition, a thermonuclear burn initiated in a hot spot in the fuel generates a self-sustaining burn wave that propagates into the surrounding fuel without additional energy input.

Figure 1 shows a succession of laser facilities that were constructed at LLNL to study the physics and technology of ICF and a broad range of High Energy Density Science (HEDS). These facilities included Janus,[7] Cyclops,[8] Argus,[9] Shiva,[10] Novette,[11] and Nova.[12,13,14] They were largely devoted to the study of ID and their results were central to establishing the Functional Requirements and Primary Criteria (FR&PC) of the NIF. The major US facility for the study of DD is the Omega Upgrade Facility[15] at the University of Rochester. Omega has also been used for ID experiments since Nova was decommissioned in 1998.

Located at Lawrence Livermore National Laboratory (LLNL) in Livermore California, the National Ignition Facility (NIF),[16] shown in the cut-away view of Figure 2, is the world's largest and most energetic laser facility for research in inertial confinement fusion (ICF) and high-energy-density stockpile science (HEDSS). NIF was designed and built as an essential element of the National Nuclear Security Administration (NNSA) Stockpile Stewardship Program (SSP).[17] NIF also performs experiments for fundamental science, other national security missions, and the potential use of ICF as a source of renewable energy. The groundwork for NIF began following the 1990 National Academy of Science Review of the ICF Program.[18] This work included the Nova Technical Contract,[19,20] with a series of physics objectives to be demonstrated on the Nova laser, and the operation of a scientific prototype of a NIF beam called Beamlet.[21,22,23]

Fusion ignition at laboratory-scale is widely accepted as a grand challenge; delivering NIF, a laser capable of pursuing that goal, has been a major challenge in its own right. Two conceptual design reports (CDRs) for NIF were written in 1994, one for a 192-beam and the other for a 240-beam approach.[24] The early strategy for procurement of the NIF hardware is laid out in Reference 25. It relied heavily on procurement of components and turn-key systems from industrial suppliers. The preliminary design (Title I) completed and reviewed in 1996 laid out the specifications for many of these procurement packages. Construction of the NIF building began in May 1997. By 1999 it had become clear that no industrial bidders could be found for many of the key subsystems and that the project would be unable to meet its original baseline cost and schedule. A new management team developed a revised execution plan for the NIF project. The Secretary of Energy Advisory Board Task Force conducted extensive reviews on this plan for completing the NIF and, in FY2000, accepted the re-baseline of the NIF project.

Thousands of engineers, scientists, and technicians have been involved in NIF, first in proposing that such a massive laser might even be possible and later in designing the specialized equipment housed inside, much of it the first of its kind. Hundreds more construction personnel, employees of equipment suppliers, and testing and commissioning experts helped bring the NIF dream into reality.

The project included design, facility construction, equipment procurement and installation, and acceptance testing. Implementation was accomplished by an international collaboration among government, academia, and many industrial partners throughout the U.S. and around the world. The re-baselined NIF Project met its schedule and cost goals. In recognition of the exceptional accomplishments of the NIF team, the NIF Project was selected as the Project Management Institute project of the year in October 2010.

The NIF facility has an unprecedented experimental capability, with much of the target fabrication, cryo-support, and target diagnostics being implemented as part of the National Ignition Campaign.[26] The concepts for NIC were formulated in 2005, including two primary goals: (1) performing integrated ignition experiments that would lead to ignition and burn via inertial confinement fusion and (2) transition of NIF from project completion to a routinely operating facility. The National Ignition Campaign (NIC) was an integrated national effort and a partnership among the following institutions: Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), University of Rochester's Laboratory for Laser Energetics (LLE), and General Atomics (GA). Other key contributors include Massachusetts Institute of Technology (MIT), Lawrence Berkeley National Laboratory (LBNL), National Security Technologies (NSTec), Atomic Weapons Establishment (AWE) in England, and Commissariat à l'Energie Atomique (CEA) in France.

A wide range of capabilities is required to support the full-range of NIF missions. Although much of the focus during the NIC was on the requirements for ignition, because ignition is in general the most demanding of NIF's missions the NIC developed both the laser and support capabilities relevant to all the missions. Efforts following the NIC have continued to broaden the capabilities of the facility.

As reviewed in References 27 and 28, the NIC team developed an approach for the ignition campaign that is summarized in Figure 3. The target point design formed the focal point for thinking and planning for an experimental campaign. It defined the system requirements for integration of the laser, targets, diagnostics, and the facility infrastructure. With these system capabilities in place, a sequence of specialized experimental platforms was implemented for individual study of one or two different target parameters at a time. A platform consists of a combination of the target design, definition of the laser characteristics for the experiments, a set of target diagnostics selected for their ability to collect data of specific interest to the target study underway, and the configuration of the target chamber for that series of experiments. These specialized platforms could be used to both measure and guide "tuning" of physical features of the target and the laser in pursuit of optimizing the implosion of the fuel. Finally, the optimized target and laser parameters were applied to deuterium–tritium ice layer (cryo-layered) targets; the implosions of these targets were then assessed with a variety of diagnostics.

Section II of this article provides a summary of the physics campaigns being conducted or planned on the NIF. It includes a discussion of the ICF Ignition Campaign as well as a brief introduction to a number of other campaigns for High Energy Density Stewardship Science (HEDSS), Fundamental Science (FS), and Inertial Fusion Energy (IFE). The NIF experiments in support of the ignition goal were a central element of the NIC. A detailed review of these experiments can be found in Reference 27, and an extended synopsis of key results is given in Section IIa. Section II also provides the context for Sections III-VII that give an overview description of the capabilities developed for enabling pursuit of experiments for the multiple NIF user communities. These sections serve as an introduction to the rest of the papers in this issue of *FS&T*. Section VIII provides a summary and conclusions.

II. PHYSICS CAMPAIGNS ON THE NIF

Since it was established as a construction project in 1995, NIF has been envisioned as a national user facility. Built in support of the NNSA Stockpile Stewardship Program (SSP), most of the experiments center around the SSP, either for Inertial Confinement Fusion (ICF) research or for HEDSS. NIF also performs experiments supporting other national security applications and fundamental science.

As NIF transitioned to a user facility, management structures were developed to serve its broad user community. Shot proposals from the different user groups are peer reviewed for technical excellence and reviewed by the facility for execution and machine safety.

II.A. ICF

In discussing the definition of ignition, the 1997 NRC report[29] commented:

The definition of ignition, while seeming straightforward at first glance, is not necessarily a point of consensus within the community of ICF researchers. Therefore, the committee has adopted an operative definition for the purposes of this report. The shape of the yield curve is cliff-like in that fusion yield increases very rapidly, from near zero to its full value, over a relatively small range of incident energy. A plot of fusion yield as a function of other relevant drive parameters (such as laser uniformity or capsule surface finish) would exhibit a similar structure. This curve leads to the operative definition of ignition adopted by the committee: gain greater than unity.

However, there are two diagnosable milestones on the yield curve. At a gain of about 0.1, energy deposited by fusion alpha particles is sufficient to double the central temperature. At a gain of about 0.3, fusion reactions occur over a sufficient region to induce propagation of the thermonuclear burn into the denser, colder, outer fuel."

The key challenges for the ignition campaign are:

1) Designing an integrated laser/target system that can achieve fusion ignition and burn propagation

2) Achieving the conditions required for ignition in the presence of uncertainties in the physics models

3) Gauging progress toward the achievement of those conditions throughout the ignition campaign

These challenges and their responses defined the framework of the NIC. Addressing questions such as these and developing answers while at the same time working in parallel to develop subsequent requirements for the laser, target fabrication, and future experiments has been the focus of research in inertial confinement fusion (ICF) for more than four decades. The approach for responding to the three challenges of the NIC was addressed in a Special Topics Section in 2011 in *Physics of Plasmas*[30,31,32,33] and in a comprehensive review of the NIC published in 2014 (References 27 and 28). The description below follows that in Reference 27.

The NIC target point design was developed using the world's most advanced high-performance computational systems, combining algorithms, models, and large-scale simulations with an extensive database of target physics information gathered over the course of several decades of ICF research. A key capability in advancing research in ICF has been the rapid advance in computer capabilities as shown in Figure 4. This growth in computer capabilities mirrors the growth in laser capabilities. Since the completion of the conceptual design report for the NIF in 1994, the capabilities of computers available for modeling the physics of ICF have increased more than five orders of magnitude as measured by flops/sec. This advance in computer capability was driven by the Advanced Simulation and Computing (ASC) initiative[34] in the NNSA Stockpile Stewardship Program and has been an essential element of the ignition campaign on the NIF.

NIC targets are driven to implode by x rays generated as the 192 NIF laser beams hit the walls of a high-Z cylindrical hohlraum. The high-energy laser beams enter the hohlraum through holes in the two ends of the cylinder. A schematic of the NIC hohlraum used in experiments in 2011–2012 is shown in Figure 5. The 192 beams consist of 48 "quads" of four beams each. Models for target performance often consider a quad of four beams to behave as a single ~f/8 beam. Each quad can have an individual temporal pulse shape. The quads are grouped together to form a total of eight cones, four cones in each of the top and bottom hemispheres. The cones form angles with the hohlraum axis of 23.5°, 30°, 44.5°, and 50°, and each contain 4, 4, 8, and 8 quads, respectively, per hemisphere. Quads in the 23.5° and 30° can operate at a wavelength (or color) that differs by a few angstroms from that of the 44.5° and 50.0° quads. The quads in the 23.5º cone can also operate at a different wavelength from that of quads in the 30º cone. Pulse shapes of quads in the different cones can also vary from one another. The relative brightness of beams in the various cones allows time-dependent control of the symmetry of the x rays irradiating the capsule. Also, as the slightly varying colors of the different cones interact, they create plasma gratings within the hohlraum that make it possible to transfer energy from one set of cones to another, providing an additional technique for controlling long-wavelength-radiation flux symmetry. Hohlraums used during NIC were typically filled with He gas, confined (before being hit by the laser) by ~0.5-micron-thick polyimide windows that cover the Laser Entrance Holes (LEHs).

The capsule, held in place between two, ~100-nanometer-thick films of Formvar, is made up of thin, concentric spherical shells. The outer shell, called the ablator, can be CH plastic, high-density carbon (HDC, sometimes called nano-crystalline diamond), beryllium, or another low-Z material. The ablator encloses the spherical shell of DT fusion fuel, kept solid before a shot by keeping the entire assembly at cryogenic temperatures near the triple-point of the fuel mixture. The interior of the shell contains DT vapor in equilibrium with the solid fuel layer. The DT is fed into the capsule through a 10-micron-diameter fill tube inserted into a hole in the ablator. In order to minimize seeds for hydrodynamic instabilities, the layers of the shell must be very smooth. In addition, special treatment is given to the interface between the ablator and fuel layer. Near this interface, the ablator includes concentric layers of a mid-Z dopant for absorption of preheat x-rays, thereby tailoring the temperature profile and thus the density of the ablator near its interface with the cryogenic fuel. CH ablators were used during NIC and doped with either Si or Ge for preheat protection. The initial CH point design capsules with Ge preheat dopant were used in the NIC campaign until August 2011 when they were replaced by more efficient Si-doped capsules. As part of the implosion optimization process, experiments tested ablators of different thicknesses as well as different dopant concentrations and profiles.

X rays that result from heating the high-Z walls of the hohlraum irradiate the centrally located capsule, ablating material from the spherical shell surrounding the fuel. The resulting implosion compresses and heats the fuel to fusion conditions. The x rays heat the hohlraum to a peak radiation flux temperature T_r that can range from 270 eV to above 300 eV, depending on the laser power, the hohlraum design, the capsule design, and the ablator material. As shown in Figure 5(a), the drive pulse has four precisely controlled steps. The laser power in terawatts (TW) and the hohlraum temperature in electron volts (eV) generated by the laser drive are also given as a function of time in Figure 5(a). These shapes are necessary for compressing the DT fuel without generating unacceptable shock preheat and entropy in the fuel. The DT fuel must remain almost Fermi degenerate in order to minimize the pressure required for a given compression. The fuel is initially compressed by three shocks, followed by a nearly adiabatic compression. Maintaining adequately low entropy for the entire fuel volume requires that each shock be carefully controlled in strength and launch time.

As the imploding fuel approaches the center of the shell, the kinetic energy of the implosion is converted to energy of compression of the fuel within the shell; the imploding shell stagnates, forming a central hot spot surrounded by a denser shell of cold fuel. If the density and temperature of the central hot spot are sufficiently high, thermonuclear reactions initiated in the hot spot by collisions of the D and T atoms in the fuel generate a self-sustaining burn wave in the surrounding cold fuel. This burn wave, driven by the energy deposition of alpha particles from the DT reactions, propagates without additional energy input and constitutes ignition. This burn wave is well-established in NIF ignition scale targets by the time yields reach an energy equal to the input laser energy, or yields of about 1 MJ (~3.5×10^{17} neutrons). This level of performance has been adopted as the working definition of ignition for the NIC. At this yield, the thermonuclear energy amplification produced as a result of heating by alpha particles from the DT reactions would be 70–100 times the yield that would be produced by heating from compressive work alone without alpha deposition.

A sequence of experimental platforms used during NIC was designed to measure the target response to variations in a number of specific laser/target parameters in search of optimum conditions for implosion of the fuel. These "tuning" studies were designed to meet the second challenge listed above, finding optimum implosion conditions in the face of uncertainties in the physics models. The basic set of surrogate "physics targets" developed for the specialized platforms used during NIC are described in detail in the article "Target Development for the National Ignition Campaign" also in this issue of *FS&T*. These targets include:

- Symmetry capsules (for study of x-ray drive and optimum hot-spot symmetry or shape)
- Re-emit targets (for study of early time symmetry)
- Keyhole targets (for study of shock timing for minimizing the fuel entropy, or adiabat)
- Convergent ablator targets (for study of the trade-offs between velocity, ablated mass, and mix)

Insights gained from work to optimize target and laser parameters using these surrogate targets were then applied to cryo-layered implosions. Target performance during these integrated experiments was assessed using a wide range of diagnostics. Results of these experiments supported meeting the third challenge listed above, gauging progress throughout the ignition campaign.

Other experimental platforms have been developed since the end of NIC including a 2D variant of the Convergent Ablator target, designed to measure the shape of the imploding shell, and a variant of the keyhole target, for measurement of the growth of hydrodynamic instabilities. A more complete discussion of these targets is available in the NIC Review Article published in *Physics of Plasmas*.[27,28]

In July 2009, shortly after NIF project completion and demonstration of the laser with an output energy of 1 MJ, NIC began executing a series of experiments. The first experiment using a cryogenic target (a gas-filled symmetry capsule) was conducted in September 2009, and the first implosion containing cryogenic layered fuel (a mix of tritium, hydrogen, and deuterium) was completed in September 2010; both of these experiments demonstrated the integration of the complex systems required for an ignition campaign. Precision capsule optimization experiments began in May 2011 after qualification of the surrogate physics platforms for optimizing specific performance parameters had been completed and after technical problems associated with condensation on the LEH and with cryo-layering of the fuel had been encountered and solved. By the end of NIC on September 30, 2012, sixteen months later, significant progress had been made in controlling key implosion parameters—radiation drive, shape, velocity, adiabat, and mix—all in cryogenic layered experiments.[35,36] A detailed review of results from the NIC has been published in *Physics of Plasmas* (Reference 27).

Throughout NIC, progress on the experimental campaign has gone hand in hand with advances in NIF capabilities. A key element in the progress toward ignition has been integration of many technical improvements into the experimental platforms, including:

- Steady increases in laser energy and power (simultaneously) needed for extended drive of the capsule. During the March and April 2012 experiments, the NIF laser routinely delivered pulse energies of 1.45–1.7 MJ with powers over 400 TW. In July 2012, NIF delivered an ignition pulse with the full NIF design energy and power of 1.8 MJ and 500 TW.
- A steady increase in the number of diagnostics, with accompanying improvements in their performance. Approximately 60 diagnostic systems are now in use.
- Significant advances in the precision of target fabrication and the ability to characterize the targets used for experiments.

Diagnostics, targets, and laser capabilities have reached the performance levels needed for a systematic optimization of ignition-scale experiments. Progress in the NIC experimental campaign can be summarized as follows:

- Peak hohlraum temperatures have been achieved that exceed the 300 eV point design goal with coupling of the laser energy into the hohlraum staying nearly constant at 84±2% for laser energies from 1.2–1.7 MJ. The use of higher-albedo, Au-lined, U hohlraums further improved peak temperatures by ~10 eV to above 320 eV.
- Hot-spot symmetry meeting ignition specifications has been achieved using a combination of power balance, a wavelength difference between the inner and outer cones, and an additional wavelength difference between the two inner cones.

- Shock timing experiments have demonstrated the accuracy needed to achieve the point-design adiabat.
- The dependence of implosion velocity on ablated mass has been accurately measured and is consistent with code simulations within the error bars over a range of peak–inferred fuel velocities up to those approaching the point design velocity of 370 km/sec.
- By systematically optimizing the shock timing and peak-power part of the laser pulse shape, NIC experiments have demonstrated an areal fuel density of ρr ~1.15 g/cm^2, which is about 75% of that specified for the point design. The total areal density of the imploded core is in excess of 1.6 g/cm^2 when the ρr of the remaining ablator is included.

Although significant progress was made during the NIC, the performance of cryo-layered implosions fell short of that required for ignition and well-below that of calculations:

- As the NIC experiments moved toward implosions with optimized shock timing and extended drives adequate for achieving higher pressure and higher fuel ρr, the observed levels of mix of ablator material into the hot-spot became significant. For the implosions that achieved the highest density and the highest pressure, significant mix of ablator material into the hot spot limited implosion velocities to about 300 km/sec, below the 370 km/sec velocity of the point design. Study of the impact and mitigation of hydrodynamic instabilities that lead to mix is a key research effort for moving the ignition program forward.
- Although peak pressures reached about one third of that required for ignition, the yield from all implosions was often a factor of 10 or more below 1D calculations. 1D calculations predict pressures of about 2 to 3 times higher than those observed

experimentally. Large-amplitude, low-mode asymmetry is a leading candidate for explaining at least some of the reduced pressure seen in these experiments. Better understanding of the source of low-mode asymmetry and of measures for mitigating it during implosions are key areas of research for going forward.

3D calculations that incorporate information on low-mode asymmetry as well as models for the impact of the capsule support tent, the capsule fill hole, and measured surface roughness come closer to predicting observed performance. The fidelity of the models to experimental data is rapidly evolving., although to date these 3D calculations still tend to predict pressures, compressed fuel density, and yield that are generally too high, and to predict mix of ablator material into the hot spot that is too low.

As shown in Table 1, there were over 1,000 laser shots during the NIC campaign. Approximately 70% of these shots were devoted to improving laser performance and developing the target diagnostics capability. Approximately 20% of the shots were devoted to ICF physics experiments while the remaining 10% of the shots were experiments for a combination of High Energy Density Stockpile Science (HEDSS), other National Security Applications, and Fundamental Science.

During the NIC, there were 37 cryogenic layered implosion experiments and approximately 175 experiments using surrogate targets for measuring shock timing, shape, shell velocity, and hohlraum symmetry. A summary of progress in NIC cryo-layered implosions is shown with the open circles in Figure 6 (References 26, 27, 35, and 37). Initial experiments, begun in September 2010 prior to the start of implosion optimization, used Ge-doped capsules and performed orders of magnitude below predictions from integrated simulations. After a sequence of experiments for optimizing shock timing and implosion symmetry and after changing to Si-doped capsules that were found to be more efficient, capsule yields approaching 10^{15} neutrons were obtained. These yields were still nearly an order of magnitude below the predictions of 1D simulations. The next set of experiments extended the laser pulse duration in pursuit of improving performance by going to higher compression and higher velocity. Although these experiments achieved increased density and fuel ρr, the yield was reduced and the onset of significant mix into the hot spot appeared. The leading hypothesis for explaining this result, formulated during analysis of the experiments, is that low-mode implosion asymmetry and hydrodynamic mix were degrading performance more than predicted by the simulations at the time.

Following the conclusion of NIC, pursuit of ignition and burn continues to be a major effort on NIF. Experiments since the end of NIC have focused on improving our depth of understanding of the physics that controls implosion performance. New experimental platforms have been developed to investigate detailed physics of the implosion. Previously, symmetry on NIC was only adjusted by measuring the symmetry of the hot spot at peak compression. These images only measured the shape of the hot central fuel. Under a variety of circumstances, the shape of the surrounding cold fuel can differ significantly from that of the central hot spot. Asymmetry of the cold fuel is capable of reducing confinement and areal fuel density. Thus, one new platform provides two-dimensional radiography of the imploding shell. These radiographs have shown that the implosions on NIC had a significant fourfold P4 Legendre mode in-flight asymmetry. More symmetric in-flight implosions can be produced if the hohlraum length is increased by 0.7–1.0 mm from the standard NIC length of 9.4 mm.[38] These inflight radiography experiments also showed that the capsule support structure, or tents, that holds the capsule in place provided a seed larger than anticipated for hydrodynamic instabilities. Effort is under way to reduce the mass of the tents to reduce the seed for these effects.

Another set of experiments for studying the underlying physics controlling ignition implosions has centered on measuring the growth rate of hydrodynamic instabilities. In these experiments, controlled perturbations are imprinted onto an ignition capsule ablator.[39] The capsule is mounted onto a reentrant cone and placed in the center of a hohlraum in the Keyhole geometry. The reentrant cone allows access to the shell interior for x–ray radiography of the imploding shell. The hohlraum is driven with a typical ignition pulse, with eight of the beams used to drive a backlighter target that produces 4–7 keV resonance-line x-rays. Preliminary results indicate that the growth factors in CH capsules using the NIC ignition pulse are comparable to those predicted by simulations. Also, these experiments show that implosions using pulses that produce a higher adiabat implosion have lower growth rates as predicted by simulations.[40]

Recent experiments have begun exploring the performance of higher adiabat implosions. These experiments use Si-doped CH capsules similar to those used for NIC experiments and are driven with laser pulses that have a "high foot",[41] a higher initial pulse than shown in Figure 5(a) used for the NIC experiments. The initial pulse produces a shock that sets the initial adiabat of the cryogenic fuel. The higher adiabat implosion is more stable to ablation front hydrodynamic instabilities, a fact confirmed in experiments as discussed above. Although higher adiabat implosions are more forgiving to the effects of hydrodynamic instabilities, they are also calculated to produce lower areal fuel density and reduced 1D performance relative to the initial NIC targets. Initial experiments show good performance relative to calculations. The results are summarized as the solid circles in Figure 6. Implosions with high-foot pulse shapes have produced yields approaching 10^{16} neutrons and have performance that is up to ~50% of that predicted by simulations. Very importantly, these experiments indicate that a significant fraction of the yield is from self-heating by alpha deposition, a first for ICF implosions. Experiments are being planned that will extend these experiments to lower adiabat and higher yield while aiming to maintain the current favorable mix behavior.

Experiments have also begun to explore the performance of alternative ablators. High-density carbon (HDC) and Be ablators are calculated to produce more efficient implosions than CH ablators. HDC (diamond) capsules have been fabricated.[42] Initial experiments with gas-filled HDC capsules[43] have demonstrated high implosion velocities and good performance. Good performance has also been obtained in the first DT layered implosion with an HDC capsule. Plans are underway to extend these initial experiments to implosions that could achieve ignition. Designs for Be ignition experiments are also being developed;[44] initial experiments began in August 2014.

II.B. HEDSS Experiments

Experiments on NIF contribute to the enduring U.S. Nuclear deterrent in the absence of additional nuclear testing[45] by:

- Elucidating key weapons performance issues left unanswered when testing stopped.
- Validating physics models incorporated in Advance Simulation and Computing (ASC) numerical simulation design codes upon which the SSP relies.
- Maintaining aspects of test readiness.
- Recruiting, training, and retaining weapons program personnel.

The improved numerical simulation codes, which will be benchmarked and validated against underground nuclear test results and experiments at the NIF, will enable nuclear weapon scientists to improve the fidelity of nuclear weapon performance simulations and reduce uncertainties in U.S. and foreign nuclear weapon assessments and U.S. warhead certifications. NIF is unique in its capabilities to provide data needed by the SSP because of its ability to produce extreme energy density conditions over reasonably large volumes combined with high-resolution diagnostics.

The acquisition of weapon-physics-relevant data in the high-energy-density (HED) physics regime to validate these physics-based models is essential to the development of predictive capabilities for stockpile applications. Data generated from both ignition-relevant and non-ignition HED experiments are categorized into four main topics: nuclear, thermonuclear, radiation, and output and effects.

The *nuclear* area focuses on the physics during the implosion phase of the system. The most important physics areas are the material properties at these conditions, the implosion hydrodynamics, and the nuclear properties (such as nuclear cross sections) at the pressure and temperature conditions similar to those at the centers of giant planets and stars.

During the *thermonuclear* effort, materials are studied as they turn into hot plasma and are subject to strong dynamic interactions, similar to those at the center of stars and that of a supernova. The dynamic behaviors and symmetry have impact on the efficiency of burn performance. Key HED efforts in this area include acquiring hydrodynamics data at various conditions to validate the models and to assess the integral performance of burning plasma in the presence of perturbations and symmetry issues.

The *radiation* effort focuses on the study of radiation transport in modern system configurations and the validation of opacity models at relevant temperature and density conditions. Key HED efforts in this area are the measurement of radiation propagation in various geometries to validate the radiation flow algorithms incorporated in the codes and obtain data to validate first-principle opacity models, which govern the absorption and transmission of x rays in nuclear devices.

Numerical modeling of radiation transported in a nuclear weapon is complicated by the extremes in conditions encountered and the geometrical configurations that must be addressed. NIF provides a platform for conducting experiments that allows the validation of radiation numerical algorithms in these relevant regimes.

Because the opacity of material governs the absorption and transmission of x rays in a nuclear explosive device, opacity data of materials is a necessary input for codes that simulate the transport of radiation in weapons, a key factor in device performance. First-principles computer models for calculating opacities are beyond the scope of today's largest supercomputers. Instead, models that generate opacity data use approximate methods and give inexact data with difficult-to-quantify uncertainties as input into the large simulations. Opacity experiments to date have been very important in improving opacity theory and models, but they have been restricted to lower temperatures and densities than those critical to nuclear-phase weapon performance. NIF provides the conditions required to obtain opacity data useful for significantly advancing models in the relevant high temperature regime.

Efforts on *output and effects* focus on the post explosion phase where the nuclear weapon releases x-ray, neutron, and gammas on the intended targets. Key HED efforts include developing relevant sources that model weapon output and utilize these sources to study the coupling of radiation for effects assessment and validation.

NIF has already provided critical data to the SSP. Results from a series of non-ignition experiments on NIF, and precursor experiments on Omega and Z validated a physics-based theory and simulation capability that was a major factor leading to the resolution of a longstanding anomaly left unanswered when underground testing was suspended. Data obtained from NIF showed that the theory and simulation capabilities developed to remove this anomaly were correct. The elimination of this anomaly represents a significant accomplishment for the SSP, eliminating one of the key technical reasons for having to potentially return to underground testing and enabling production decisions in support of stockpile sustainment.

II.C. Fundamental Science

There is much synergy among the different user communities for developing experimental capabilities. For example, many of the platforms developed for ICF are used for HEDSS and fundamental science experiments. The same platform is used for studying EOS as part of the HEDSS Program and for fundamental science experiments. Of course diagnostics are used across all of the different users and much of the target fabrication development is applicable to many different research areas.

An example of the cross-connection of different research areas involves the use of radiochemical detectors. Solid Radiochemistry Collectors have been developed by ICF to measure activation products produced in ICF ignition experiments. The collectors are discs of solid material placed near the target. After the shot the collectors are taken to a nuclear counting facility to measure the activated products. During counting, activated Au (gold) debris from the hohlraum wall is found as well as activation products from the initial disc material. The ratio of Au activation products depends on the flux of low-energy neutrons present at the hohlraum wall. The low-energy neutrons are produced when 14 MeV neutrons created by DT fusion events are down scattered in the high-density capsule shell. The activation measurements indicate the presence of excited nuclear states of Au.[46] NIF is the only facility in the world that can produce low-energy neutron flux densities high enough to allow study of excited nuclear states.

Another example of a cross-connection between ICF and fundamental research is provided by a fundamental science experiment to measure the equation of state of carbon up to a Gigabar along its Hugoniot.[47,48] This experiment is a collaboration of scientists from the University of California at Berkeley, GSI Darmstadt, SLAC Accelerator National Laboratory, AWE, and LLNL. It uses a hohlraum platform developed for ICF ignition experiments with the ICF capsule replaced by a solid CH sphere. X-rays from the hohlraum ablate the outside of the sphere to produce a spherically convergent shock in the sphere. The velocity of the shock front is measured using x-ray radiography tools developed for ICF. The shock front is tracked by the increased absorption of the x-ray backlighter as the density of the material increases due to the shock front. When the shock converges at the center, an x-ray flash is observed. By fitting the trajectory, the equation of state of CH can be extracted.

For FY2015, the NIF facility has allocated 18 days of facility time for a wide range of fundamental science experiments. These include experiments to:

- Obtain equation of state (EOS) data for carbon and iron, for the first time, in high-density and relatively low-temperature conditions of the giant planetary interiors. Six NIF shots on ramp-compressed diamond have attained the record-breaking pressures (up to 5 TPa) and temperatures conditions characteristic of the deep interiors of the giant planets and super-Earth exoplanets. The data has been analyzed, and the major findings have been submitted to *Nature* for publication.
- Develop in-situ powder x-ray diffraction and determine the crystal structures of highly compressed carbon phases. The project is progressing well toward its goal and is fielding the x-ray diffraction diagnostic, TARDIS, on the NIF. Combining with the VISAR (a continuum shock wave propagation probe), the TARDIS (an atomistic crystal structure

probe) will provide the most fundamental insight into shocked/ramp-compressed/released solids.

- Use temporally shaped NIF laser pulses to measure the equation of state for cryo-H_2 (and/or D_2) over a wide range of pressure-temperature-density states relevant to planetary and astrophysical conditions. The project clearly deals with a wide range of intriguing scientific issues, ranging from the condensed-matter physics of quantum solids to high-energy warm dense matter to the Mott insulator-metal transition to shock-induced ionization.
- Measure equation of state for materials of interest in the Gbar regime and demonstrate X-ray Thomson scattering measurements on heated and compressed matter states at high pressures that are accessible with the NIF hohlraum drive.
- Explore hydrodynamics relevant to the Eagle Nebula using multiple hohlraums in parallel, staggered in time to reach pulse lengths approaching 100 ns.
- Explore fundamental science question in the deeply non-linear phase of the ablative Rayleigh-Taylor instability. The behavior of the ablative Rayleigh-Taylor (RT) instability in the nonlinear phase is relatively unexplored, and the proposed experiments are designed to shed some light on the nonlinear evolution.
- Study radiative effects on the RT instability that are relevant to supernovae interacting with the ambient medium. Modeling results show reduced RT growth in the radiative shock case.
- Explore the production and measurement of collisionless shocks.

- Utilize ride along experiments, which do not require dedicated shots, to study nuclear physics in plasmas produced on the NIF where the photon, electron, and neutron densities rival those encountered under supernova conditions.

II.D. Inertial Fusion Energy

Achievement of ignition and gain is a pre-requisite for demonstrating the potential of ICF in the field of civilian power generation, whether for process-heat or electricity supply purposes. This application area, known as Inertial Fusion Energy (IFE), was identified as one of the primary missions for the NIF in the original "justification of mission need," signed in 1993 by Secretary of Energy Admiral James Watkins. This is in part due to the significant national security issues associated with energy supply, along with the potential of IFE to offer emission-free generation of energy at a large utility scale, using a scientific and technological approach that is highly synergistic with the wider mission space of the Department of Energy.

IFE requires a continuous stream of ignition events, with a gain of 30 to 100, at a repetition rate of 5–20 Hz. As such, it requires substantial technological advances that lie outside the scope of the NIF project.[49,50] What the NIF does provide, however, is the opportunity to demonstrate the physics performance of an igniting capsule along with the required system configuration and tolerances in laser and target parameters. This is essential information with regard to enabling a credible design and assessment process for a future power plant. Most importantly, the NIF is designed to operate at a level of fusion output that would be full-scale for a power production plant; thus in principle, information from NIF can be utilized directly without extrapolation.

Conceptual design work performed to date for IFE power plants has shown that their physical layout and mode of operation can be decoupled from many of the details of the fusion target design. Taken together with the highly parallel and modular nature of a laser-based IFE plant, this means that substantial progress can be made in the design, testing, and integration of individual sub-systems during a period when the precise details of an optimized target design are still being explored on the NIF. For example, the fact that an IFE plant needs to operate at high repetition rate requires that a fundamentally different approach be adopted for the laser design—with a leading option including the use of diode-pumped solid state lasers.[51] The decoupled nature of the laser operation and target performance means that such changes can be made without affecting the value of the ignition demonstrations performed at the NIF.

An IFE plant would, however, impose additional constraints on the target deisgn that would require explicit validation at full scale on the NIF. Such tests could be considered as a future role of the facility following the demonstration of ignition. For example, an IFE-relevant target would need to use alternate materials in the hohlraum,[52] would require the development of new techniques for production of the cryogenic fuel layer, and would require enhanced mechanical and thermal protection consistent with repeated injection.[53,54]

Overall, the prospects of achieving ignition and gain on the NIF provide a compelling opportunity to investigate the viability of embarking on a future program to develop an integrated power plant based on the ICF method of energy production. Such an approach would be highly complementary to the magnetic fusion concepts being explored by the ITER project and could enable timely progress in this much-heralded field.

III. THE NIF LASER

III.A. Overview and Description of the Laser

In order to make NIF a facility capable of achieving the ICF and HEDSS objectives, a wide range of scientific and technological challenges had to be overcome.

The NIF laser delivers more than 50 times the energy of any ICF laser previously built. However, more impressive than its raw power and energy is the precision and reproducibility with which NIF operates. NIF is able to deliver highly flexible pulses on each quad of beams with temporal variations of over a factor of 400 to an absolute precision of within a few percent of that requested for any given experiment and with a shot-to-shot reproducibility that is also less than a few percent. This level of precision and reproducibility is far beyond that achievable on any other ICF facility. The systems engineering approach and the disciplined systems integration implemented in the design and construction of the NIF was core to the successful achievement of the technical requirements necessary to support the laser and target experimental systems.

The entire NIF facility was designed and constructed to provide an extremely stable optical platform. Early in the design process an exhaustive set of specific performance requirements was established to assure that the integrated experimental facility would be capable of delivering the precision laser pulses required by the target. This included requirements of every system within the NIF including the building structure, environmental conditions within the building, the laser and target chamber structures, Reliability/Availability/Maintainability (RAM) requirements for every system, and strict performance specifications for every component and assembly. During construction, compliance with these requirements was carefully monitored. Changes were made under the guidance of a strict configuration management and control process. As a result, NIF experiments are now being conducted successfully with exquisite precision and reliability.

The paper titled "Description of the NIF Laser"[55] provides a top-level overview of the architecture, systems, and subsystems of NIF. It describes in detail how they partner with each other to meet the complex demands of ignition implosions and describes how laser science and technology were woven together to bring NIF into reality. Major subsystems of NIF described in this paper include the Injection Laser System, the 1ω Main Laser Amplifier (both of these operate in the near infrared at 1.053 μm), and the 3ω Final Optics (that delivers light to the target in the near ultraviolet at 0.351 μm). The technical motivations and past experiences of similar systems (at smaller scale) are summarized as background for the description of these major subsystems of NIF. Development of the physical optics codes that were used for optical design of the NIF beamlines began during construction and operation of the LLNL laser systems that preceded NIF, pictured in Figure 1. A descendent of this code forms the calculational core of the Laser Performance Operations Model (LPOM), now a principal interface between users and NIF. LPOM, with its many tracking and reporting roles supports both users and operators of the laser. As it manages the workflow for calculation of the laser beam power and energy as a function of space and time for each quad, it takes into account the energetic performance of individual NIF beamlines (which each have unique amplifier gains and optical losses). LPOM is a key component of NIFs ability to operate reproducibly at high power and energy. During NIC, tools were provided to support all phases of executing a shot on NIF—planning and scheduling an experiment, setup, execution, data archiving, visualization, and analysis. An important part of this capability is provided by LPOM and its interfaces with the NIF Integrated Computer Control System.

III.B. Optical Damage Avoidance

In the end, the high performance limit of all lasers is set by optical damage. The demands of inertial confinement fusion have pushed lasers designed as ICF drivers into this limit from their very earliest days. The first ICF lasers were small, and their pulses were short. Their goal was to provide as much power to the target as possible. Typically, they faced damage due to high intensity on their optics. As requests for higher laser energy and longer pulse lengths appeared, new kinds of damage also emerged, some of them anticipated and others unexpected. The paper, “Damage Mechanisms Avoided or Managed for NIF Large Optics”[56] reviews the various types of damage to large optics that had to be considered, avoided to the extent possible or otherwise managed as the NIF laser was designed, fabricated, and brought into operation. It has been possible for NIF to meet its requirements because of the experience gained in previous ICF systems and because NIF designers have continued to be able to avoid or manage new damage situations as they have arisen.

Among the challenges to the successful deployment of the NIF, a few stand out for their potential to impact the availability of NIF as an experimental system. These include avoiding flashlamp-induced damage to the large amplifier slabs and management of damage to the NIF final optics.

III.C. Cleanliness of NIF large amplifiers

Cleanliness of the NIF laser is of paramount importance for conducting high-energy experiments. Small particles or residue located in the laser can cause unwanted amplitude modulation in the laser beams and damage to the optics. Stringent cleanliness requirement were established early on in the design/construction process using extensive damage testing results conducted at LLNL and other research facilities.

As an example, important tests carried out between 1997 and 1998 in the Amplifier Module Prototype Laboratory (AMPLAB) and in Beamlet (the physics prototype of NIF) from 1995 to 1998 showed that generally accepted amplifier-cleaning procedures would be inadequate for the NIF. Work in both AMPLAB and Beamlet was a cooperative effort between the Commissariat à l’Energie Atomique (CEA) in France and NIF. The paper “Cleanliness for the NIF 1ω Laser Amplifiers”[57] reviews the search for the source of the damage observed in the AMPLAB and

Beamlet experiments and describes the solution employed in NIF for avoiding flashlamp-induced aerosol damage to its 1ω amplifier slabs, a problem that had plagued all large lasers prior to the NIF. Without the cleanliness insights described here, this type of damage would have far exceeded tolerable levels. A critical "last-minute" change to the design of the NIF amplifier support hardware involved diversion of 10% of the flow of clean dry air (CDA) originally intended only for flashlamp cooling to provide a flow rate of 30% of the main amplifier enclosure volume per minute vertically across the slabs. As NIF is operated, this system is turned on after every flashlamp shot to remove any aerosol particles that may have been created during the shot. The addition of this capability to the NIF was funded as part of the UK Shot Rate Enhancement Program (SREP).

Overall airborne cleanliness inside the NIF 1ω laser enclosures is Class 100 or better, and surface cleanliness on each optic must be maintained between Level 50 and 300 depending on the optic. Further, non-volatile residue (NVR) levels cannot exceed 0.1 $\mu g/cm^2$ on several optics types. These stringent conditions are very difficult to achieve under any condition but are especially challenging for a laser system that is as large and complex as NIF. To achieve these conditions, every surface internal to the laser was meticulously cleaned. To cleanly install each of the thousands of optics, a comprehensive set of installation procedures was also established to assure that ambient contamination would not enter the laser beam path. Numerous hardware systems were built to protect and transport optics from the Optics Assembly Building to the NIF and then cleanly install the meter-sized optics quickly into the laser. The success of these systems has been crucial to NIF for meeting the performance requirements and shot rate required by the experimental programs.

III.D. Optics Recycle Loop

In order for NIF to meet its goals for the capital and operating cost of its optics, it was necessary to develop advances in optics manufacturing and in operational procedures that would allow it to operate at a fluence level more than an order of magnitude greater than operating fluences of previous ICF facilities.

Techniques for production of the optics were developed in partnerships between LLNL and optics suppliers that had started years earlier with work on the systems shown in Figure 1. Advances made during NIF construction resulted in components that consistently met rigorous optical specifications including the ability to withstand intense laser fluence with minimal optical damage. The fused silica final optics operating at 3ω are both the most expensive optics in NIF and the most susceptible to this type of damage. Even though the optics being delivered to NIF today have very damage-resistant surface finishes, under intense laser illumination, it is still possible for small damage sites to form on their surfaces and these can then grow in size on subsequent laser shots. The 3ω Optics Recycle Loop embodies a strategy for economically maintaining and reusing the final optics. It has been very effective in supporting and enabling routine high-energy, high-power experiments on NIF. Implementation of the loop strategy was guided by an LLNL institutionally supported research program that explored understanding of basic phenomenology and mitigation of laser-induced optical damage. This research led to significantly better methods for arresting damage initiation and developing higher quality and more robust bulk materials for optics fabrication as well as advancing finishing techniques and post-fabrication processes that further improve damage resistance. This research also guided the selection of technologies and processes implemented as part of the Loop strategy during NIC and enabled the NIF 3ω optics to operate consistently and predictably at a level significantly above their damage growth threshold.

Improvements in the critical technologies needed for operating the loop, the improved surface finishing, in-situ optics inspection, and damage growth mitigation have enabled a steady increase in NIF laser performance from about 300 kJ in July 2009 to almost 2 MJ in July 2012, as indicated in Figure 7. Before this work, optical damage was a seemingly intractable problem for those designing and operating high-energy, high-power laser systems. The advancements made in understanding the causes and signatures of optical damage on a fundamental level and the development of new technologies to arrest and mitigate damage, coupled with the innovative loop recycling strategy, have positioned NIF to operate routinely in regimes denied to all other laser systems. A review of this work is given in the paper titled "Optics Recycle Loop Strategy for NIF Operations Above UV Laser-induced Damage Threshold".[58]

III.E. Optics Production for NIF

The NIF's 192 beams contain 7,360 large-aperture optics (~0.5 to 1.0 m). These include amplifier slabs, mirrors and polarizers, lenses and windows, and crystals (KDP and DKDP). Manufacturing the NIF optics required an extensive, multi-year optical materials and process development effort that began in 1995. This effort was successful because LLNL partnered with a group of well-known optical materials and optics fabrication companies located around the world. This approach was built upon a 25-year tradition of working closely with optics manufacturers to develop and manufacture the optics needed for the high-energy laser systems previously constructed at LLNL.

The approach to the multi-year, multi-vendor development effort involved four steps: (1) technology development, (2) design and construction of manufacturing facilities, (3) start-up and “pilot” production, and (4) full production. The technology development stage included not only the development of the optical materials, advanced manufacturing tools, and processes but also the advanced metrology tools needed to test and verify the performance of the finished optics. During the second step, new optics manufacturing facilities (approximately 150,000 ft^2) were designed, constructed, and put in place at the NIF vendors along with advanced processing equipment. These state-of-the-art facilities were then commissioned by the third step (i.e. pilot operations), during which time a small percentage (5–10%) of the required NIF optics were manufactured to shake-down and troubleshoot the process and verify that performance and cost goals could be met. The final step was full production, which included manufacturing the large optics needed for completing NIF at a rate required to meet the commissioning schedule of all 192 NIF beam lines. NIF is the largest optical system ever built. The production rate, quality, and cost goals adopted by the NIF Project required innovations at essentially every step.

The quality of the optics produced for NIF through this multi-year, multi-vendor effort ended up being significantly better than the specifications. The quality of the optics resulted in adding considerable design margin to the laser system. The paper “Large Optics for the National Ignition Facility”[59] reviews the efforts devoted to developing and manufacturing those optics.

III.F. Controls and Data Acquisition

The NIF Integrated Computer Control System (ICCS) is the most complex, real-time control system ever designed for scientific research. The automated control system provides reliable monitoring and control of approximately 66,000 distributed control and monitor points; the precise orchestration of these control points results in a safe, precise, and well-diagnosed laser shot. ICCS ensures that all of NIF laser beams arrive at the target within 30 picoseconds of each other and are aligned to a pointing accuracy of less than 50 microns RMS while assuring that a host of diagnostic instruments record data in a few billionths of a second. ICCS is an integrator of laser, target, and target diagnostic activities. It is the effector of moving mirrors, focusing cameras, setting filters, etc. across the multiple systems in NIF. Several million lines of code are required to efficiently conduct and evaluate the precise laser and target diagnostic alignment, test, and shot sequences.

The needs of the ignition campaign were strong motivators for work completed by ICCS. Through a host of servers, networks, databases, and storage devices, ICCS provided tools to support all phases of executing a shot on NIF, including: planning and scheduling an experiment, setup, execution, data archiving, visualization, and data analysis. The paper "Control and Information Systems for the National Ignition Facility"[60] provides an overview of these capabilities.

III.G. Performance of the NIF

After completion of commissioning, NIF steadily increased its power and energy as shown in Figure 7 (Reference 37). At the time of NIF Project completion in 2009, the laser was operating at 300–500 kJ and 200 TW of 3ω light. In the course of normal operation[61] during 2012, NIF demonstrated that it could achieve its design goals of 1.8 MJ and 500 TW of 3ω light on target in an ignition shaped pulse.

The NIF Functional Requirements and Primary Criteria (FR&PC) were established for the project during the conceptual design phase in 1994. These requirements were largely determined by the needs of the Ignition Campaign that put the most demanding requirements on the laser. Meeting the NIF Project Completion Criteria in 2009 included meeting large portions of the FR&PC. During the National Ignition Campaign, and as NIF transitioned to a user facility, its goals were expanded to include requirements defined by the broader user community as well as by laser system designers and operators. In the paper "National Ignition Facility Laser System Performance,"[62] the work done to demonstrate that NIF meets its performance requirements is reviewed.

IV. TARGET DEVELOPMENT AND MANUFACTURING

In order to meet the stringent requirements of an ignition implosion, the targets for the ignition campaign had to meet precision and reproducibility requirements that were unachievable by the handmade, best-effort targets used on earlier laser systems. Figure 8 shows the increase in the target complexity as experiments moved from the earliest laser systems to NIF. The NIC experimental plan required two classes of targets:

1) Targets used to optimize specific performance parameters (velocity, adiabat, shape, and mix), called surrogate physics targets, as described above.
2) Cryo-layered ignition targets used to assess integrated performance.

All of these targets are complex, consisting of many components that have to meet stringent specifications with tight tolerances and the need for precise alignment. The ignition target is similarly intricate with additional requirements imposed by its cryogenic fuel layer. An ignition target must also allow high-resolution diagnosis of the quality of the frozen fuel layer within the capsule.

A key challenge for target fabrication was demonstrating that all of these targets could be fabricated with the requisite precision and quality and in the quantity needed to keep pace with the experimental program. During the NIC, capabilities were established to manufacture capsules, hohlraums, and all the diagnostic and alignment components for the targets.

A graded-doped CH capsule (doped with Ge or Si) was used throughout the NIC experimental campaign on NIF. However, graded-doped Be (doped with copper) and high density carbon (HDC) capsules were developed as alternate ablators. As described in the companion paper on target development, all three materials were ultimately developed to point design specifications. Prototypes of each capsule material were assembled into full targets for layering tests; these tests showed that ignition-quality layers could be made in each capsule material. Similar advances were made in hohlraum materials. Boron-doping of the inside surface of the hohlraum material was developed to suppress Stimulated Brillouin Scattering (SBS) in the hohlraum plasma, and sputter deposited depleted uranium (DU) technology was developed to improve x-ray conversion efficiency.

Precision was maintained with new capabilities provided throughout the fabrication process from the fuel fill tube—a tenth of the size of a human hair—to the target error margin for micro-assembly of less than three microns. The engineering team developed a concept called the "thermo-mechanical package (TMP)" that maintained reproducibility of assembled target dimensions for each of the different target types and also met the cryogenic requirements for layered fuel. Throughout NIC, the agility of the target fabrication effort was stressed as technicians, scientists, and engineers were asked to quickly respond to design and tolerance changes such as capsule and ice surface smoothness. A small but very important focused technology development program, with particular emphasis on precision engineering, characterization, and applied materials research, enabled the NIC target fabrication team to meet these challenges.

As shown in Table 1, during the NIC 210 targets were used in experiments with all but 21 targets fielded at cryogenic temperatures. Of the total, 37 experiments were conducted using ignition targets with a cryogenically formed fuel layer, by far the most difficult target to fabricate, assemble, and field. The paper "Target Development for the National Ignition Campaign"[63] reviews the development of these capabilities.

V. CRYOGENIC TARGET SYSTEM

During the NIC, the hardware and processes were put into place to field cryogenic layered fuel targets at target chamber center (TCC). The Cryogenic Target Positioner (CryoTARPOS) system shown in Figure 9 is a complex, multifunctional system designed to cryogenically grow and characterize a high-quality cryogenic fuel layer inside an ignition capsule, position and align the target at TCC, and maintain layer quality until being irradiated by the NIF laser. The NIF design built on experience gained in successfully fielding a cryogenic layering system on the OMEGA facility at the Laboratory for Laser Energetics (LLE) in Rochester. To meet the full set of operational requirements, the system needed temperature control of better than 5 mK at the target, positional stability of better than 2 microns, and automated temperature control for growing the single crystal of layered fuel. A three axis high-resolution radiographic imaging system provides the images required to support the layering and characterization steps.

The process for growing Deuterium-Tritium layers has two basic steps.

- The first step involves setting the inventory of fuel necessary to achieve the desired layer thickness and then freezing it within the capsule. To fill the capsule through the fill tube, the hohlraum temperature is held approximately 0.25K above the melting temperature of the hydrogen mixture. This ensures that liquid enters the capsule shell. During filling, the height of the liquid inside the shell is monitored and proceeds until a pre-calculated height is achieved. Once the required liquid height has been achieved, the temperature is lowered several K over a few seconds. This causes the DT mixture to solidify in the shell and fill-tube and prevents further change in the amount of DT in the capsule.

- The second step involves melting back the now solid fuel to a single crystal seed and then slowly decreasing the temperature to grow the crystalline layer. Each of these cycles takes on the order of 24 hours, with several iterations usually required to attain a high quality layer. Synchrotron diffraction and quenching studies during the NIC established that high quality layers are single crystal, often with isolated defects that are low-angle grain boundaries.

It initially took several weeks to grow and field the first acceptable layer on CryoTARPOS, and the process was heavily dependent on continuous support by engineers and scientists. Over the course of the NIC, significant effort was invested in refining the processes for growing spherical, ultra-smooth hydrogen fuel layers while keeping the number of small isolated defects below that allowed by the ignition specification. Continuous improvement in the metrics of growth and the growth characterization processes has resulted in near-real-time determination of layer quality with a high degree of confidence. The ability to make an early decision regarding layer quality and understanding when to stop and restart the ice layering process resulted in a considerable increase in shot rate for layered implosions. Optimizing hydrogen crystal growth conditions to achieve the highest quality layers and developing a quick and effective method for evaluating layer quality were among the most critical accomplishments during NIC. The paper "Cryogenic Target System for Hydrogen Layering"[64] reviews development of these capabilities.

VI. DIAGNOSTICS AND EXPERIMENTAL SYSTEMS

During the NIC years, an array of precision target diagnostics were developed and implemented in NIF. These diagnostics are critical for progress on optimizing key capsule performance characteristics, including velocity, symmetry, and entropy (fuel adiabat) while simultaneously minimizing the impact of hydrodynamic instability and laser plasma instability effects. Development of the NIF diagnostics plan began early in the planning phase for the facility.[65] NIF is now equipped with approximately 60 diagnostic systems. These include optical, x-ray, and nuclear diagnostics (gamma ray, activation, and neutron diagnostics) Together, these diagnostics provide approximately 300 channels of data that support the experimental campaigns and measure laser and target performance. Developing, installing, calibrating, and performance testing NIF's diagnostic systems was a major focus of the NIC. One of NIF's two Dante soft x-ray spectrometers is shown in Figure 10. Many instruments implemented on NIF have state-of-the-art adaptations of previous diagnostics developed for the nuclear test program or for other laser facilities. An essential element of the overall plan for NIF diagnostics was ensuring that several diagnostics could measure the same characteristic (observable) to provide redundancy and ensure measurement accuracy. Given the diversity of experimental requirements and space constraints around the target chamber, many of the instruments are designed to be removable and exchangeable; the use of standardized Diagnostic Instrument Manipulators (DIMs) by several of the NIC partners has meant that the removable diagnostics could be easily tested at other facilities such as OMEGA before installation on NIF. A steady increase in the number of diagnostics and improvement in their performance over the course of the NIC has supplemented the quantity and quality of data gathered from every experiment.

Laser capabilities that enhance diagnostic capabilities are also expanding. Recently, the capability to delay beams up to 100 ns for producing x-ray backlighters was installed for radiography of hydrodynamic instability experiments. NIF is now installing the capability to produce short-pulses for high-energy x-ray radiography. Advanced radiographic capability (ARC) is being installed on one NIF quad.[66] Each beam in the quad is divided into two ARC beamlets that propagate pulses independently to target. ARC uses chirped pulse amplification to produce pulse energies up to 1.5 kJ per beamlet followed by vacuum grationg compression to temporally compress the pulses to durations adjustable from 2 to 50 ps. The first four of the eight ARC beamlets are planned to be operational in 2015.

The article "The National Ignition Facility (NIF) at the Completion of the National Ignition Campaign (NIC) September 2012"[67] reviews current NIF diagnostics and discusses some of the new diagnostics being planned.

VII. OPERATIONAL CAPABILITIES

NIF operations demand that every aspect of an experiment be meticulously controlled: setting up the laser and diagnostics, aligning the target, executing the experiment, and collecting and archiving the data. The objective is to provide safe, high quality, and cost effective stewardship capabilities over the 30-year expected operational lifetime of the facility.

Because the use of radioactive and/or hazardous materials such as tritium during routine NIF operations is a requirement of NIC, the necessary safety systems to monitor, contain, and process these materials (e.g. tritium processing system and the hazardous waste management area to handle contaminated equipment) were put in place along with the systems to contain the radiation and neutron yield, and activation radiation. NIF, its personnel. and environmental protective systems (shield doors, radiation monitoring equipment, and interlock systems), in conjunction with training and work authorization processes, have proven to be highly effective at protecting workers, the public, and the environment as well as sensitive equipment and instruments.

Throughout the NIC, NIF operations staff worked to evaluate and improve operational processes and capabilities, with the intent of maximizing facility reliability, availability, and maintainability while at all times preserving safety. For instance, a reliability-centered maintenance program was deployed to reduce equipment failure rates, improve equipment repair and response times, anticipate problems, and look for windows of opportunity to conduct routine maintenance. Using a reliability-centered process for making maintenance resource allocations allowed NIF personnel to identify and focus on critical functions that impact the shot cycle and shot rate. Safe and efficient operational processes and capabilities developed during the NIC have enabled NIF staff to maximize the data return on each shot performed.

The paper "Operations on the National Ignition Facility"[68] reviews the NIF operational capabilities and procedures.

VIII. SUMMARY AND CONCLUSIONS

Progress continues toward the goal of achieving ignition. Experiments since the end of NIC have focused on understanding the implosion physics for improving target performance. These include measurement of the inflight symmetry of the imploding capsule and quantitative measurement of hydrodynamic instability growth factors. Implosion platforms have been developed that have reduced instability growth and are therefore more stable with respect to mix. In experiments to date, performance of these implosions is generally within a factor of 2–3 of that predicted by simulations with measured yields approaching 10^{16} neutrons. In recent experiments, more than half of the yield is estimated to be due to self-heating by alpha deposition, a first for ICF implosions. Target designs have been developed for alternative ablators such as HDC and Be that are potentially more efficient, and experiments are underway to test these materials.

NIF is a fully operational facility supporting experiments for ICF and HEDSS as well as fundamental science and other national security missions. It has demonstrated that it meets design goals of 1.8 MJ and 500 TW of 3ω light on target in a shaped ignition pulse and can perform at design levels as part of routine operations. This high level of performance is a result of a number of advances for maintaining optics performance operating at design fluences. NIF has developed a vast array of experimental capabilities and has commissioned over 60 different laser and target diagnostic systems. It routinely fields targets with cryogenically layered fuel for ignition experiments and has developed a number of other experimental platforms for use by its diverse user community. Additional capabilities continue to be developed such as the short-pulse, high-energy x-ray backlighting capability provided by four ARC beamlets expected to be operational in 2015.

NIF has transitioned into an international user facility for supporting its users in SSP, fundamental science, and other national security missions. The NIF team has developed and is working to continually improve its peer review process for ensuring that world-class science is conducted in the facility. Unique and unprecedented results have already been acquired in every NIF user program, and new campaigns are being proposed and planned that will further extend our knowledge of unexplored regions of high-energy-density physics.

TABLE 1. NIC shot summary

Type	Specific Purpose	Cryo	Layer	Warm	Total
Target shots-Program Data	NIC	152	37	21	210
(314 = 30%)	HEDSS			80	80
	Nat'l Security Applications			13	13
	Fundamental Science			11	11
Target shots-Capabilities	Target Diagnostics Commissioning/Calibration			110	110
(152 = 15%)	Laser Commissioning/ Conditioning			42	42
Laser shots only	Optics Performance/ Conditioning			138	138
(578 = 55%)	Laser Performance Laser Calibration			204 236	204 236
Total		152	37	855	1044

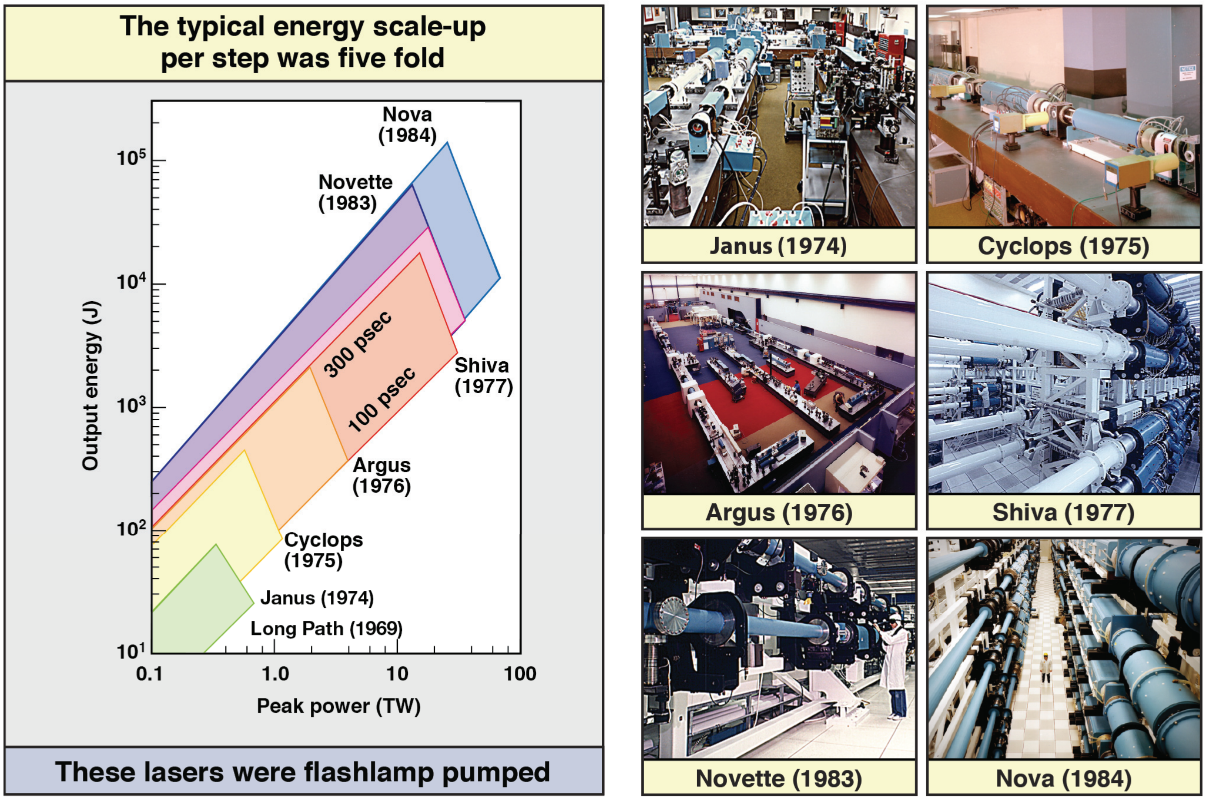

Fig. 1. LLNL built a series of laser systems of ever-increasing power and energy for fusion research, preparing the way for the NIF.

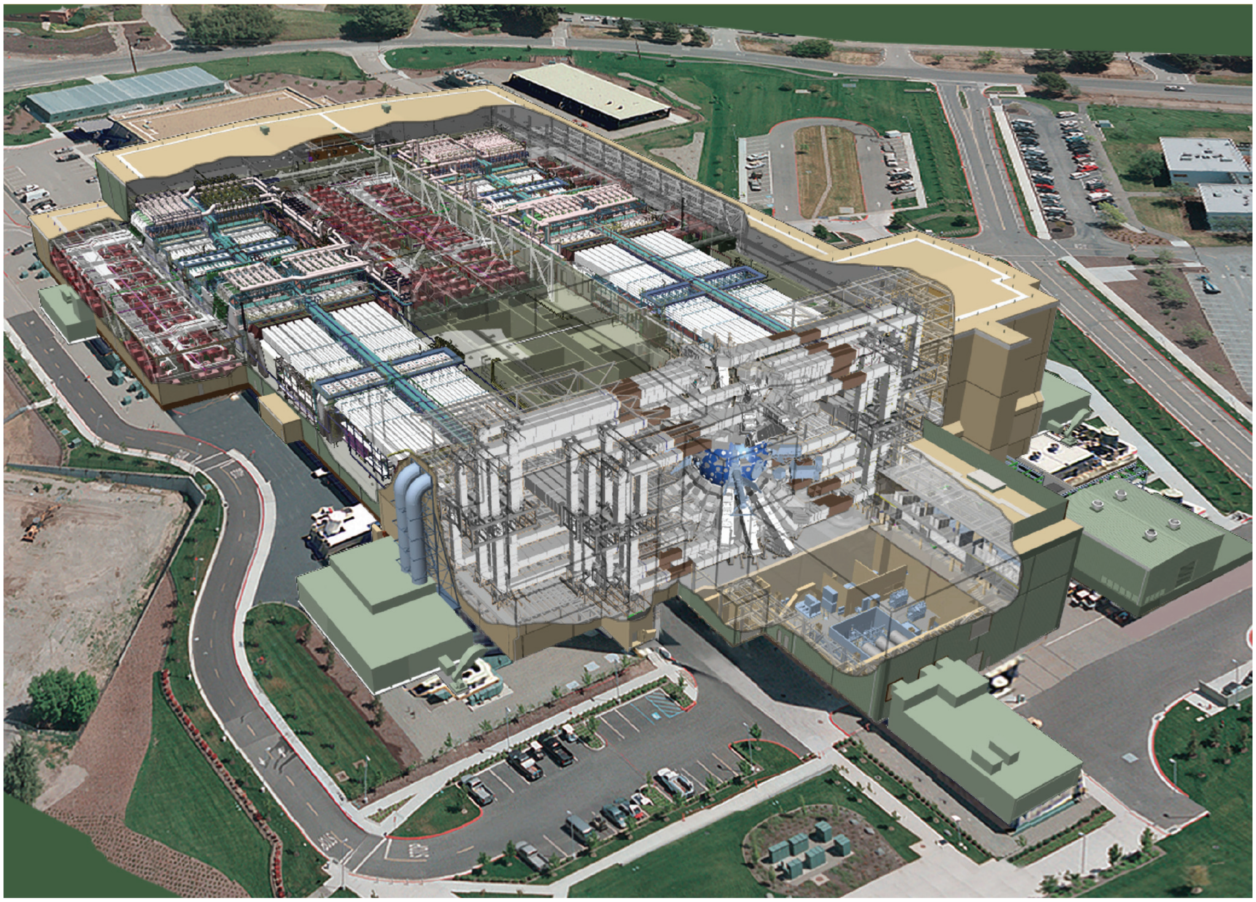

Fig. 2. A cut-away view of the NIF laser facility. The footprint of the building covers an area equivalent to just over three football fields. NIF is currently configured for the study of indirect-drive ICF targets. In NIF, 192 converging laser beams heat a ~1 cm hohlraum to a radiation temperature of ~300 eV.

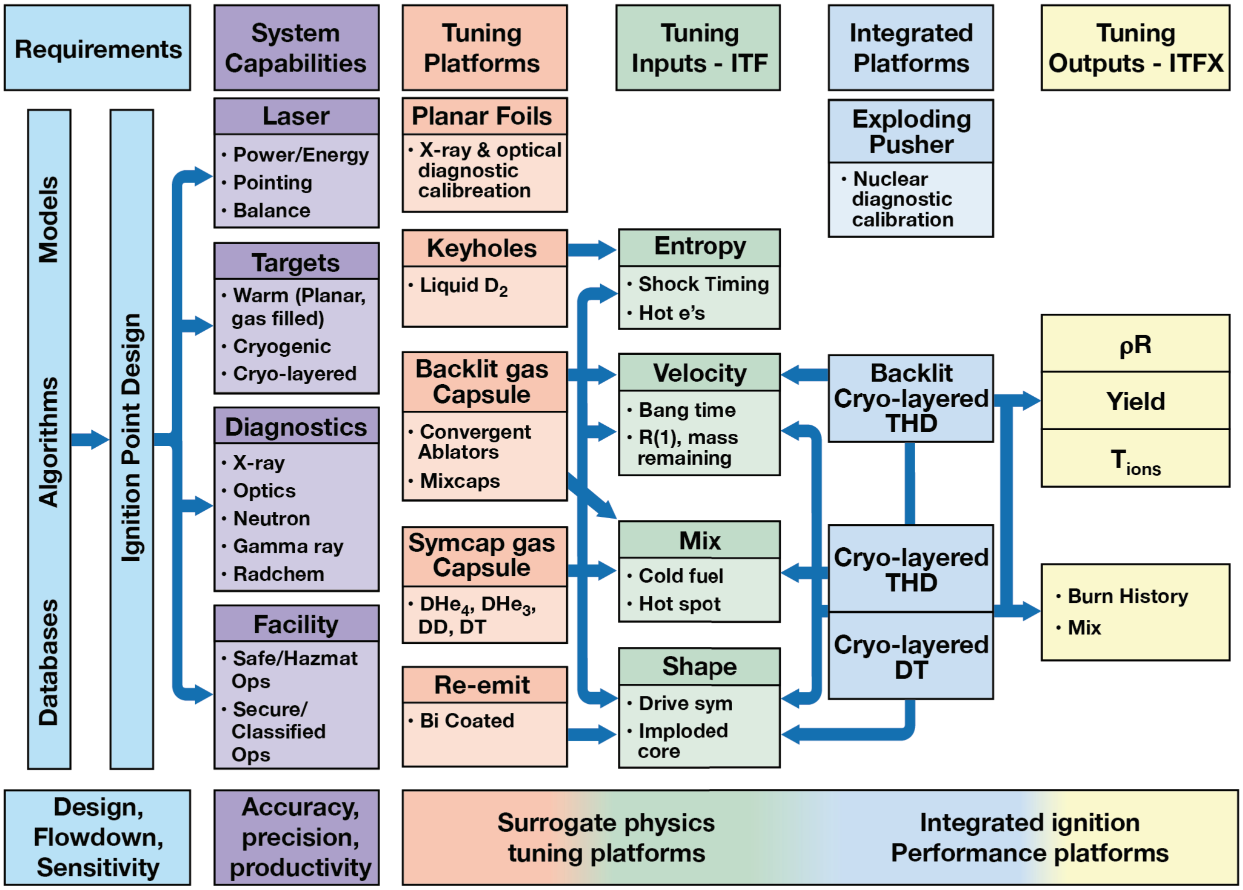

Fig. 3. The NIC Framework - Requirements established by the Point Design determine the required system capabilities. These capabilities enable the development of implosion optimization platforms and the fielding of implosion optimization (tuning) experiments. The tuning experiments yield optimized laser and target parameters for the integrated implosion platforms with output performance measured by a wide array of diagnostics. (Reprinted from Physics of Plasmas 21, 020501 (2014) by permission of AIP)

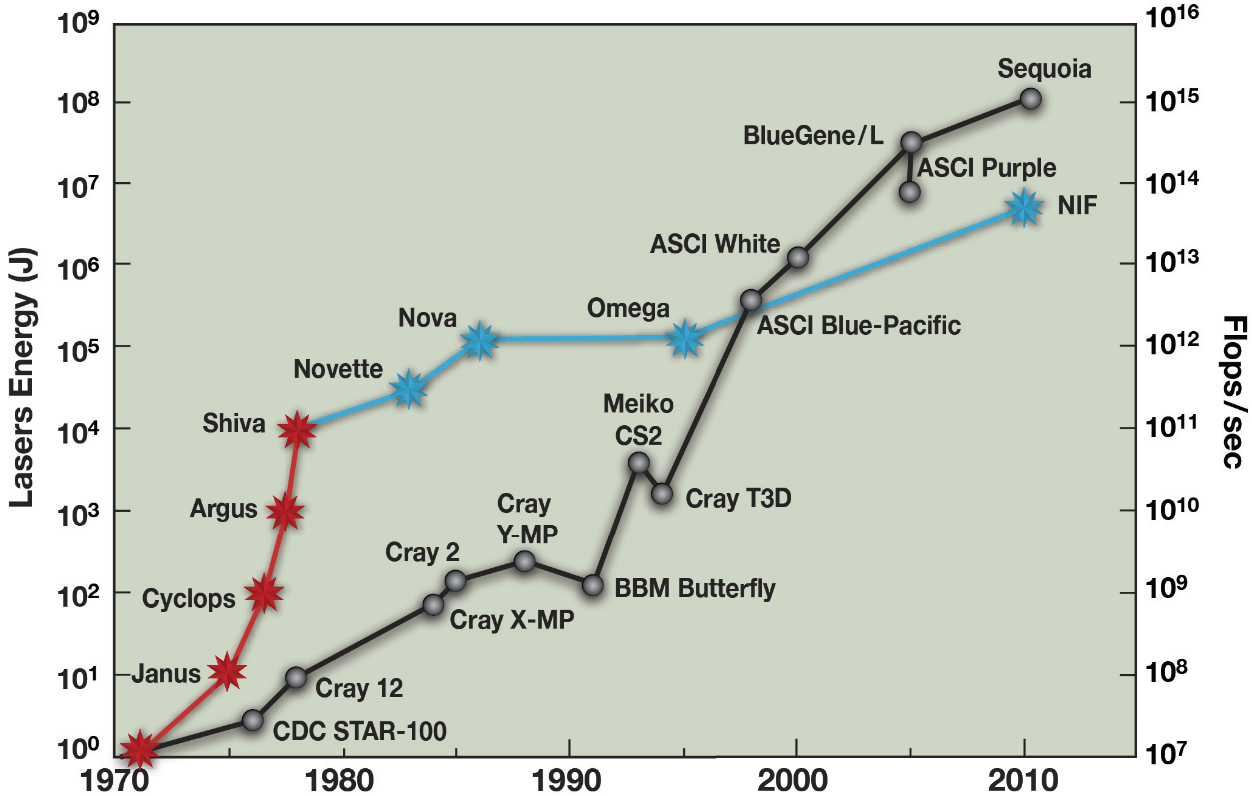

Fig. 4. Lasers and computers have experienced an explosive growth in capability in the past 4 decades.

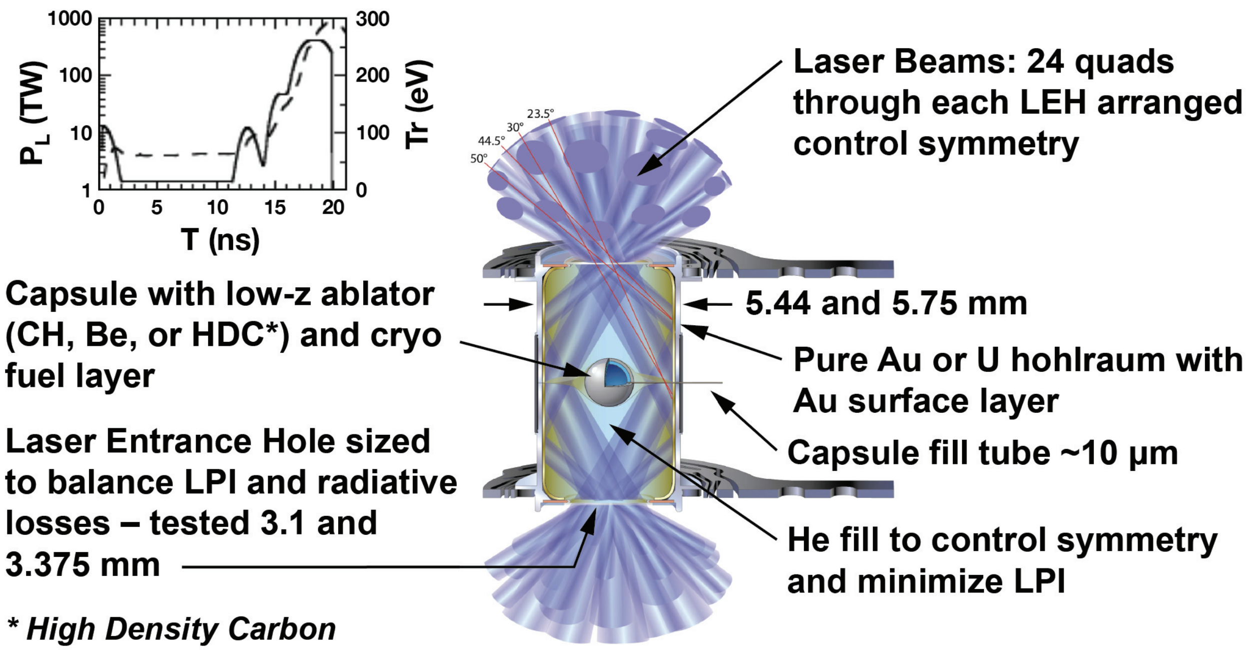

Fig. 5. (a) The laser pulse shape showing the laser power (PL) in terawatts (TW) and the radiation temperature (T_r) in electronvolts (eV) reached at that power versus time in nanoseconds (ns). (b) Schematic of ignition target design, highlighting key features and options for hohlraum and capsule materials.

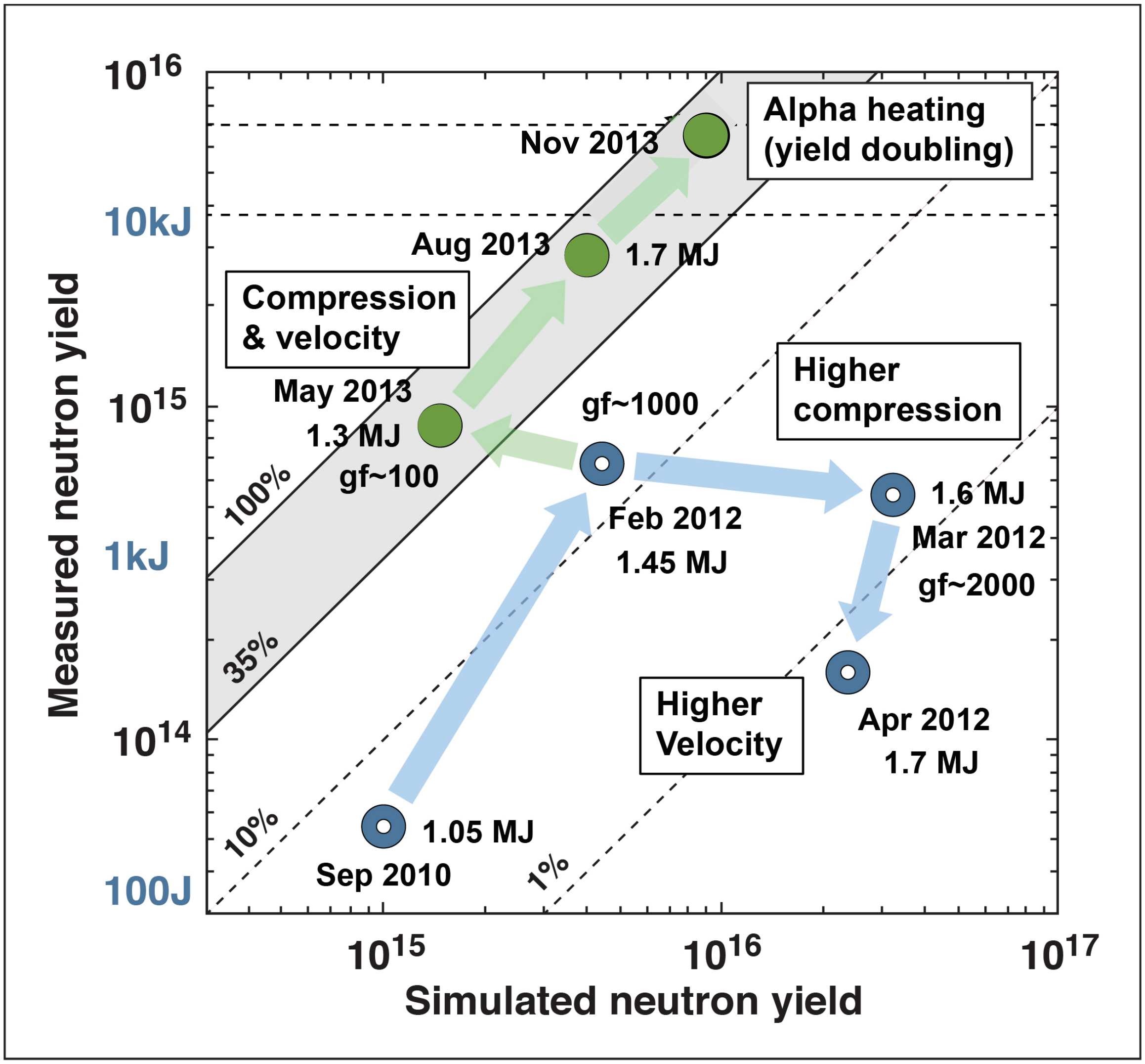

Fig. 6. Progress toward ignition is shown as measured neutron yield versus yield predicted by simulations. Open circles indicate progress during NIC with low adiabat implosions. Solid circles indicate progress made recently with high adiabat implosions (From Reference 37, Reprinted by permission of IOP Conference Series (IFSA 2013)).

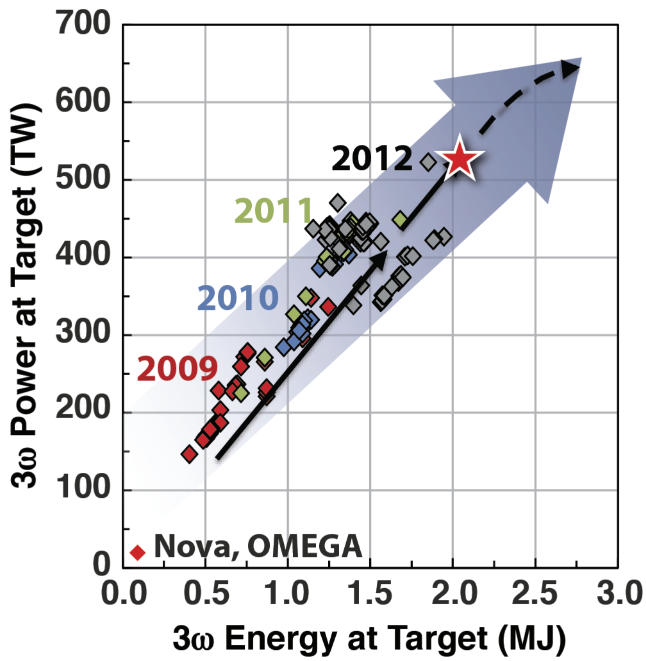

Fig. 7. Progress in power and energy on NIF increased steadily during the NIC, with performance exceeding its design goal of 1.8 MJ and 500 TW in 2012 (from Reference 36, Reprinted by permission of IOP Conference Series (IFSA 2013)).

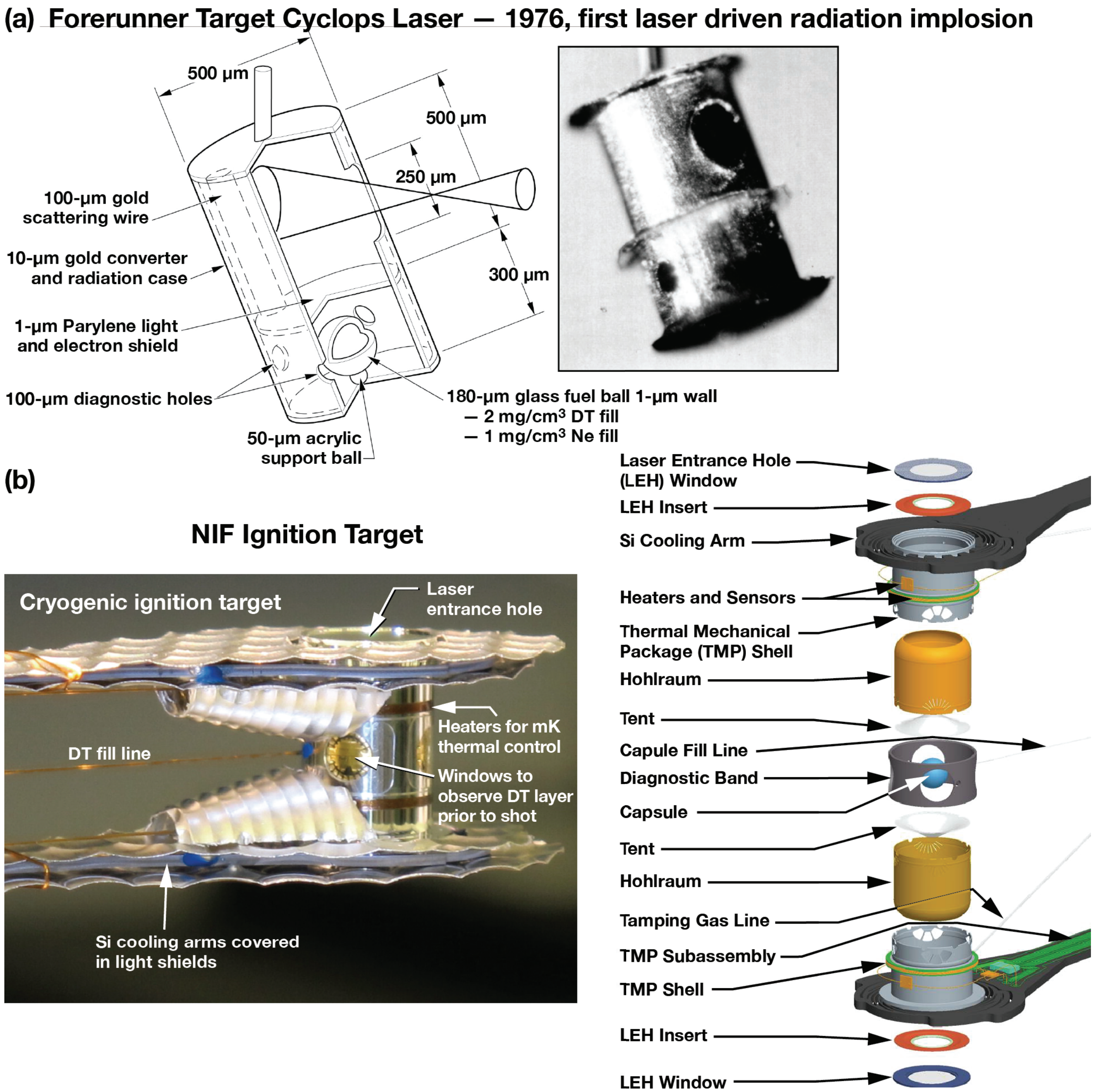

Fig. 8. Targets have evolved to meet the demands of increasingly complex goals. (a) Schematic and picture of the Au hohlraum and glass microballoon used on the Cyclops laser for the first radiation driven implosion. (b) Picture and schematic of a NIC ignition target.

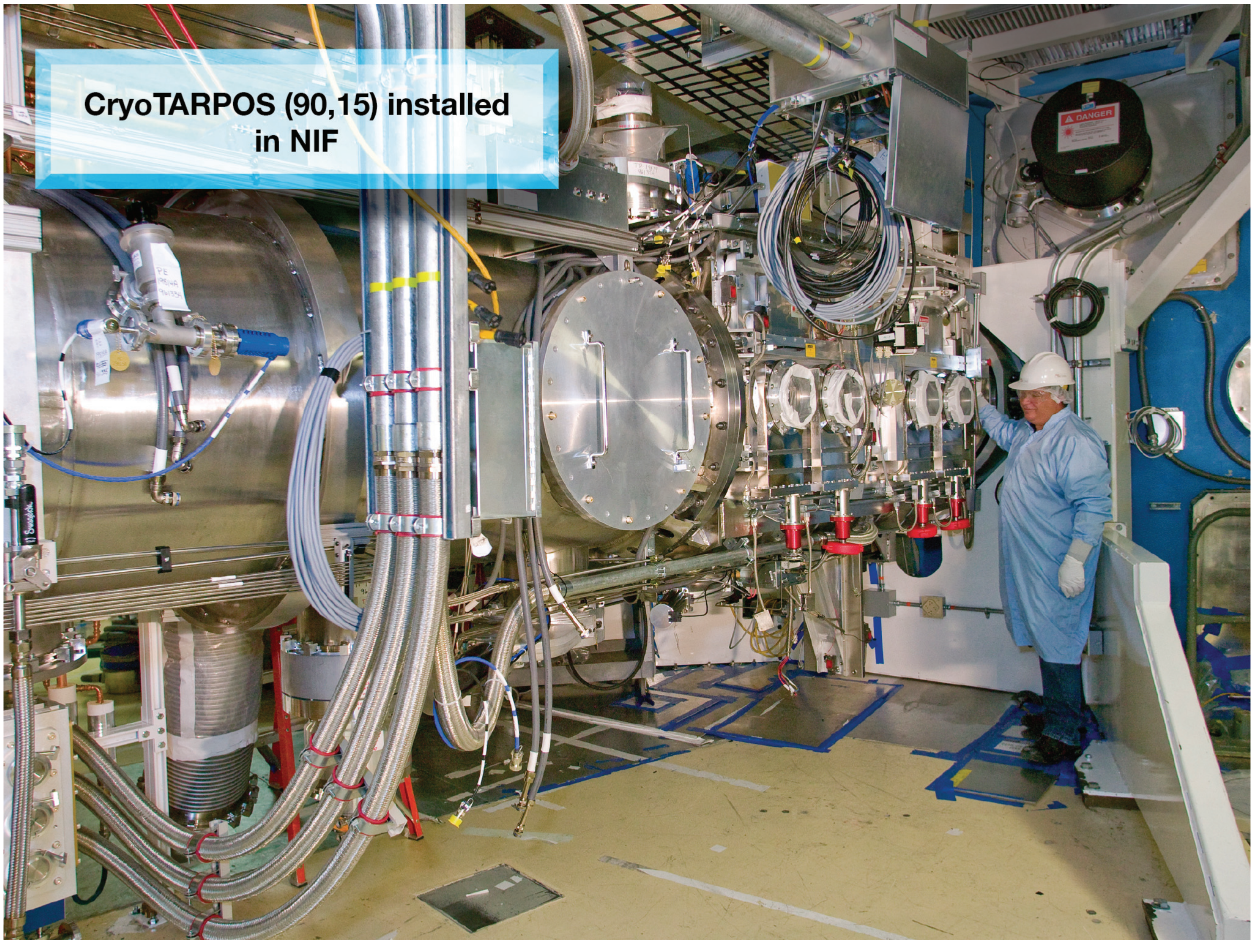

Fig. 9. CryoTARPOS, a positioner and layering system located just outside the target chamber, enables the precise formation of the cryogenic layers needed within the capsules of ignition targets.

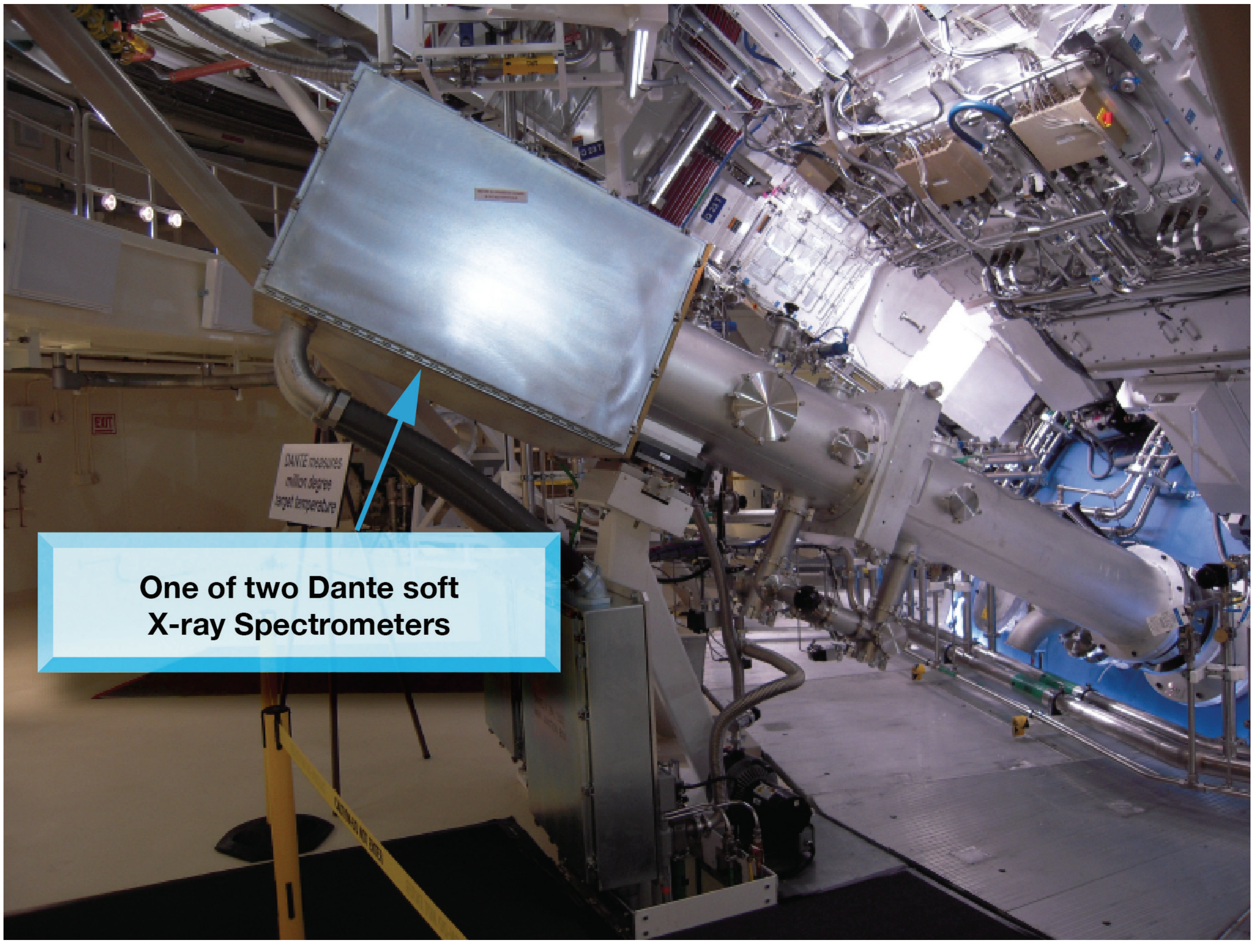

Fig. 10. NIF's Dante soft x-ray spectrometers are a primary diagnostics for measuring the x-ray drive generated in hohlraum targets.

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